Experimental Sensitivity for Majorana Neutrinos
Produced via a Z Boson at Hadron Colliders

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We present experimental sensitivity for the production of a fourth-generation Majorana neutrino (N) via an s-channel Z boson $Z \to NN \to W\ell W\ell$ at hadron colliders. This channel has not been studied for the Tevatron dataset with $\int \mathcal{L} = 5$ fb^{-1}, where we find that a single experiment could significantly extend current 95% C.L. mass lower limits, to $m_N > 175$ GeV/c^2, or report 3σ evidence for the N if $m_N < 150$ GeV/c^2. With 5 fb^{-1}, a single LHC experiment at $\sqrt{s} = 10$ TeV could expect to set a 95% C.L. mass lower limits of $m_N > 300$ GeV/c^2, or report 3σ evidence for the N if $m_N < 225$ GeV/c^2.

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INTRODUCTION

The study of a fourth generation of quarks and leptons has undergone a renaissance. While earlier studies [1] claimed that the fourth generation was ruled out by experimental data, a recent analysis [2] has shown that the constraints can be satisfied by appropriate choices of mass splittings between the new fourth generation particles. Furthermore, the existence of the fourth generation can help to address certain discrepancies between the Standard Model and experimental results in the b-quark sector[3–8], leading to a revival of interest in this possibility (see [9] for a review).

In view of the imminent arrival of LHC data, it is of particular interest to search for signals of these fourth-generation fermions at hadron colliders. Such analyses have been performed for the t' and b' quarks. CDF has searched for the t' quark [10] using the CKM suppressed decay $t' \to qW$ and for the b' quark [11] using the process $b'b' \to t\bar{t}W^-W^+$ which can yield like-sign dileptons. These searches have set limits of 311 GeV for the t' [10], and 338 GeV for the b' [11] (but see [12]). The LHC will discover or exclude fourth generation quarks up to about a TeV [13–15].

However, few detailed analyses have been performed in the lepton sector. By analogy with the first three generations, one might expect the leptons of the fourth generation to be lighter than the fourth generation quarks and in particular, the fourth generation neutrino might be expected to be the lightest new particle. It is of interest to see if this neutrino can be found at colliders.

Past searches for fourth generation neutrinos have mainly been performed at lepton colliders. In particular, LEP II has looked for neutrinos produced in the process $e^+e^- \to Z \to NN$, where the neutrinos subsequently decay via the process $N \to l^\pm W^\mp$. No excess of such events was found, which placed a limit of about 100 GeV for Dirac neutrinos decaying to electrons, muons or taus. For Majorana neutrinos the corresponding limits were about 90 GeV if the neutrino decayed either to electrons

or to muons, and about 80 GeV if it decayed to taus.

Theoretical analyses of fourth generation neutrinos at hadron colliders [16–19] have focused on the process $q\bar{q}' \to W^\pm \to Nl^\pm$ where the fourth generation neutrino is produced in association with a light charged lepton. This process has the significant advantage that only one heavy particle is produced, which increases the mass reach considerably. Furthermore, the neutrino will decay through $N \to l^\pm W^\mp$ which will produce the low-background like-sign dilepton signature in half the events.

However, the production cross-section for this process depends on the mixing between the fourth generation with the first three generations due to the $W \to lN$ vertex. In many models, this mixing angle can be small; for example, if the mixing is generated by GUT or Planck-scale suppressed operators, the angle may be as small as 10^{-11} [12]. For mixing parameters smaller than about 10^{-6}, the neutrino production rates in this channel are too small to be observable at colliders [16]. In models with small mixing angles, the dominant production mechanism becomes pair production through an s-channel Z, for which the production rate is model-independent. These signals have been studied at various benchmark points for the LHC [20] and for future linear colliders [21].

However, the analysis of the s-channel Z process has not been performed for the Tevatron. In this Letter, we present a sensitivity study for the Tevatron and argue that the LEP limits on Majorana neutrinos can be significantly improved with an analysis of the data already taken. It would be of great interest to perform a full analysis of this data. We also perform a similar study for the LHC, which can probe the parameter space to much higher energies.

PRODUCTION AND DECAY

We consider an extension to the standard model by a fourth generation of fermions and a right-handed neutrino. The mass term for the neutrinos can be written

as

$$L_m = -\frac{1}{2}\overline{(Q_R^c N_R^c)} \begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c. \quad (1)$$

where $\psi^c = -i\gamma^2\psi^*$. This theory has two mass eigenstates of masses $m_1 = -(M/2) + \sqrt{m_D^2 + M^2/4}, m_2 = (M/2) + \sqrt{m_D^2 + M^2/4}$. In addition, the mass of the fourth generation lepton is constrained to be close in mass to the neutrinos by precision electroweak constraints [2].

We consider processes where only the lightest neutrino is produced, providing the most model-independent bound on this theory. In future work, we will study the effect of the second neutrino and fourth generation lepton. For this analysis, we treat the lepton and second neutrino as infinitely massive, corresponding to a limit where M, m_D go to infinity with $\frac{m_D^2}{M}$ fixed.

The lighter neutrino mass eigenstate is the Majorana fermion $N = N_L^c + N_L$. The coupling for pair production via the Z is through the coupling $L_Z = Z_\mu J^\mu$ where

$$J^\mu = \frac{e}{2\sin\theta_W\cos\theta_W}(\bar{N}_1\gamma^\mu\gamma^5 N_1)$$

The heavy neutrino will decay through $N \to W^\pm l^\mp$ (the neutral current process is suppressed.) Note that N can decay to either sign of lepton, giving like-sign leptons in half of the events, see Fig 1. We assume that the heavy neutrino decays promptly; this will be the case unless the mixing between the fourth generation and the first three is extremely small [12].

We consider the possible decay modes $N \to W(e, \mu, \tau)$. In a hadron collider, backgrounds to τ leptons are much larger and efficiencies are much lower than for e and μ, giving the τ decay mode little power. We consider two cases, (a) $\mu\mu$, in which the non-τ decays appear solely as muons: $BR(N \to W\mu) = 1 - BR(N \to W\tau)$; and (b) $\ell\ell$, with $\ell = e, \mu$ in which the non-τ decays appear as both electrons and muons: $BR(N \to W\mu) + BR(N \to We) = 1 - BR(N \to W\tau)$. The $\mu^\pm\mu^\pm$ mode has significantly smaller background rate than $\ell^\pm\ell^\pm$.
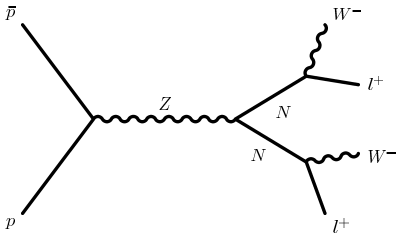

FIG. 1: Pair production of the heavy Majorana neutrino N via a Z boson, and subsequent decay $W^\pm l^\mp$.

If the N decays to ℓW, then the decay of $NN \to \ell W \ell W$ can be categorized by the decays of the W bosons. If both Ws decay hadronically, we expect approximately 4 jets. If one decays leptonically, we expect approximately 2 jets and a third lepton. If both decay leptonically, we expect approximately zero jets but four leptons. All but the fully leptonic mode, the smallest fraction, contribute to the $\ell^\pm\ell^\pm jj$ signature and allow for direct reconstruction of the N.

EXPERIMENTAL SENSITIVITY

We select events with the $\ell^\pm\ell^\pm jj$ signature:

- two like-signed reconstructed leptons (e or μ), each with $p_T > 20$ GeV and $|\eta| < 2.0$

- at least two reconstructed jets, each with $p_T > 15$ GeV and $|\eta| < 2.5$

In the case that two jets are reconstructed, the mass of the N can be reconstructed from the two jets and either of the leptons. In the case that three jets are reconstructed, we form the mass of the N from the invariant mass of the two jets which are closest to the W mass, and either of the leptons. In the case that four jets are reconstructed, the mass of the two Ns come from the ljj assignments that give the best W masses and the smallest difference between the two reconstructed m_Ns. See Figure 2.
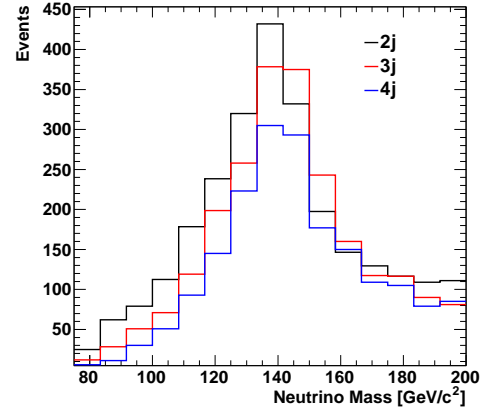

FIG. 2: Reconstructed Majorana neutrino (N) mass in events with 2, 3 or at least 4 jets for $m_N = 150$ GeV/c^2.

Backgrounds

At the Tevatron, the largest backgrounds to the $\ell^\pm\ell^\pm jj$ signature come from $W\gamma$ or WZ production or misidentified leptons [22] either from semi-leptonic $t\bar{t}$ decays or direct $W+$ jets production.

For the Tevatron, we extrapolate the number of expected backgrounds events from Ref. [22] to a dataset

with 5 fb^{-1}, use MADGRAPH [23] to model the kinematics of the events, PYTHIA [24] for showering and a version of PGS [25] tuned to describe the performance of the CDFII detector.

At the LHC, the diboson contribution includes an additional process, $qq \to W^{\pm}W^{\pm}q'q'$, which directly produces the $\ell^{\pm}\ell^{\pm}jj$ signature. For the LHC, we calculate the size and kinematics of each contribution using MADGRAPH, use PYTHIA for showering and a version of PGS tuned to describe the performance of the ATLAS detector.

Figure 3 shows the reconstructed mass shape for N pair production and for the backgrounds in the $\mu^{\pm}\mu^{\pm}jj$ case.
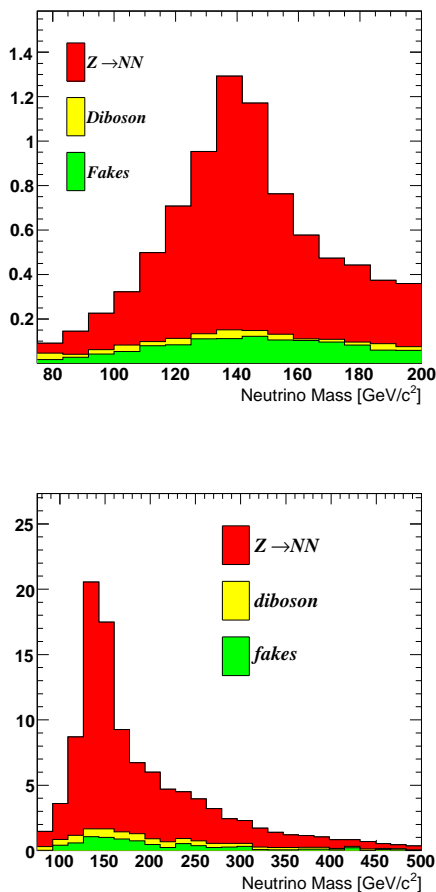

FIG. 3: Expected reconstructed neutrino mass for N production with $m_N = 150$ GeV/c^2, and backgrounds to the $\mu^{\pm}\mu^{\pm}jj$ signature in 5 fb^{-1} of Tevatron data (top) or 10 TeV LHC data (bottom).

Expected Limits and Discovery Potential

We perform a binned likelihood fit in the reconstructed N mass, and use the unified ordering scheme [26] to con-

struct frequentist intervals. If the N does not exist and no excess is seen, the median expected upper limits on the cross-section are given in Table I and Fig. 4. In 5 fb^{-1}, with BR($N \to \mu W$) = 100%, a single Tevatron (LHC) experiment could expect to set a 95% lower limit of $m_N > 175$ (300) GeV. The limits as a function of BR($N \to \tau W$) are given in Fig. 5. If the N does exist, a 3σ excess would be observed in the regions shown in Fig. 5.
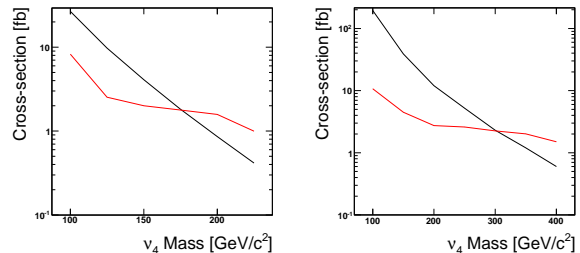

FIG. 4: Theoretical cross-section for N production and decay to $\ell^{\pm}W\ell^{\pm}W$ and median expected 95% C.L experimental cross-section upper limits in 5 fb^{-1} of Tevatron data (left) or LHC data (right), assuming BR($N \to \mu W$) = 100%.
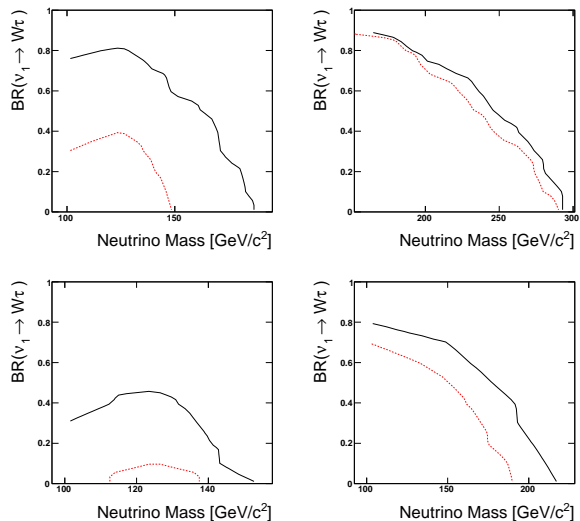

FIG. 5: Median expected 95% C.L experimental exclusion (top) or 3σ evidence (bottom) in 5 fb^{-1} of Tevatron (left) LHC data (right) as a function of BR($N \to W\tau$). Two decay cases are shown: $\mu^{\pm}\mu^{\pm}$ (black) or $\ell^{\pm}\ell^{\pm}$ (red), as defined in the text.

CONCLUSIONS

The s-channel pair production of heavy Majorana neutrinos via a Z boson ($Z \to NN \to W\ell W\ell$) is a powerful discovery mode at hadron colliders. With 5 fb^{-1} of data, the Tevatron can significantly extend the limits on such neutrinos to 175 GeV/c^2, and a 3σ evidence is possible if

TABLE I: Theoretical cross section, σ_{Theory} at the Tevatron or LHC, including branching ratio to like-sign leptons; selection efficiency ϵ for the $\mu^{\pm}\mu^{\pm}jj$ channel; number of expected events in 5 fb^{-1} of data; and median expected experimental cross section 95% CL upper limits, σ_{Limit}, assuming BR($N \to W\mu$) = 100%.

Tevatron						
Mass [GeV/c^2]	100	125	150	175	200	225
σ_{Theory}[fb]	26.7	9.8	4.1	1.8	0.9	0.4
ϵ	0.09	0.32	0.44	0.51	0.54	0.55
Yield	11.5	15.7	9.1	4.6	2.3	1.2
σ_{Limit}[fb]	8.3	2.5	2.0	1.8	1.6	1.0

LHC, 10 TeV						
Mass [GeV/c^2]	100	150	200	250	300	350	400
σ_{Theory}[fb]	195	39	12	5.2	2.3	1.2	0.6
ϵ	0.11	0.46	0.57	0.61	0.63	0.65	0.65
Yield	111.0	91.7	35.0	15.9	7.4	3.8	1.9
σ_{Limit}[fb]	10.7	4.5	2.7	2.6	2.3	2.0	1.5

the mass is less than 150 GeV/c^2. A dataset of the same size at the LHC would have an 95% C.L. exclusion reach of 300 GeV/c^2 and 3σ evidence potential for $m_N < 225$ GeV/c^2.

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